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Bifacial photovoltaic modules: measurement challenges

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Abstract

The photovoltaic market is currently competing for high efficiency cell technologies. Several of these technologies are inherently bifacial. For large commercial systems, the expected annual bifacial gain is significant, from 5 to over 15% [1]. But the lack of standardization [2] and feedback on large systems seems to limit the proliferation of bifacial modules. There are no Standard Test Conditions defined for their measurement, and no available commercial simulator that can predict their energy production. As a result, investors are still reluctant to choose bifacial technologies as an alternative to the standard monofacial ones.
In this paper, we analyse three different approaches for bifacial module performance measurements. The first approach consists in measuring both sides independently with a standard solar simulator and build an equation to extrapolate the contribution of back side illumination to the front-side power value. The second approach consists in illuminating both sides simultaneously with a specific double illumination characterization setup [3] that verifies the results of the first approach. Finally, the third approach compares outdoor and indoor behaviour of the modules.
The results presented in this paper show how the different approaches are complementary to help building up Standard Test Conditions and outdoor simulation tools for bifacial modules.

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Keywords: Photovoltaic performance ; Bifacial modules ; Measurement

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Nomenclature

PV	Photovoltaic
STC	Standard Test Conditions
Isc	Short circuit current
Pmax	Maximum power of the module
η	Efficiency
Voc	Open circuit voltage
FF	Field Factor
G	Irradiation

1. The challenge

The main challenge of photovoltaic performance characterization is to accurately predict the energy yield of a future system. The challenge has been tackled for several years, with characterization and modelling of:

- The solar resource
- The incident light on the module plane
- The module performance

For monofacial modules, the international community already agreed on the performance Standard Test Conditions. For bifacial ones, the process of standardization officially started in 2015 for SEMI and in 2016 for IEC (new project approved in February 2016). Bifaciality brings new challenges because performance depends on the module surroundings (albedo, shadowing etc.), as well as on the irradiation type (direct/diffuse). As a result, the challenge is strongly linked with both i) the front and back side contributions to the power values of the module which need to be standardized, and ii) the expected outdoor back side irradiance, which is very sensitive to the geometry of the system, that can be simulated [1].

2. The different approaches

2.1. First approach: independent measurement of both sides and extrapolations

To measure independently both sides, we first need to minimize the contribution of the photons coming from the side opposite to the light source. But bifacial modules are always semitransparent to the incident photons (between the cells, and through the cells), so back reflections are inevitable (Fig. 1).

The state of the art enlightens two methods:

SUPSI experiment [4] (Fig. 1. a):

- Characterization of the back irradiation over the back surface of the module during flash tests
- Extraction of the minimum reflected irradiation value, because it’s the one which limits the total power (0.44% of front irradiance in that case)
- Correction of measured front and back power using this minimum irradiation value and the power bifacial ratio (power back/power front)

Common solution (Fig. 1. b & c), which consists in:

- Fixing a dark screen on the back side of the module
- Considering back reflections as negligible.

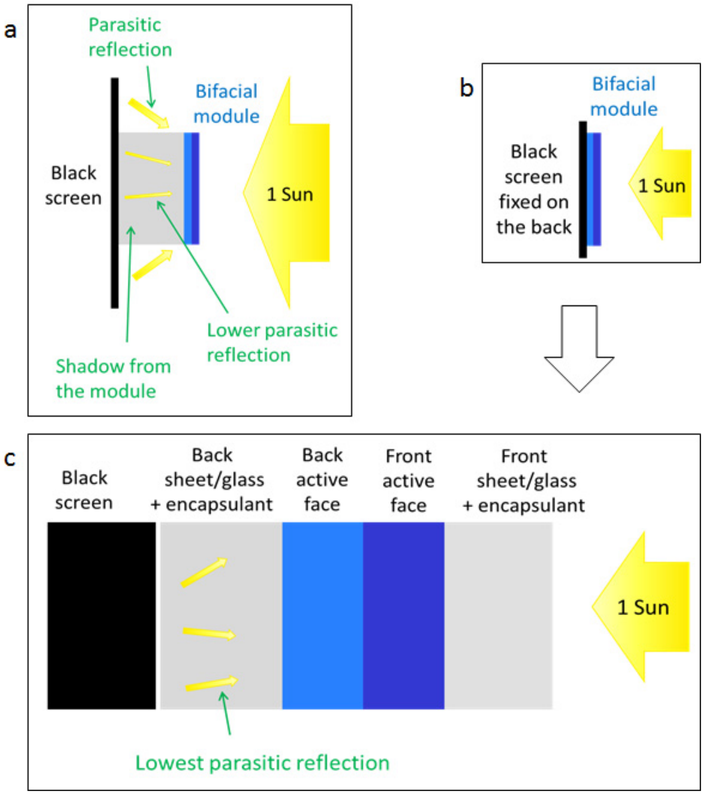

Fig. 1. (a) A standard flash room brings parasitic reflections, which can be characterized [4]. (b) Adding a black screen on the back of the module brings the reflections to a minimum. (c) Zoom on the (b) fixed screen setup: there is still a little deviation, which is more difficult to quantify

The characterisation of a very low irradiation in the first solution has a large uncertainty, depending on the exact shunt quality of the reference cell, and which is varying a lot between each cells.

The last solution is commonly used, easier and faster to implement. The deviation is certainly the lowest one, even if it is difficult to characterize. It is the solution CEA applies for this first measurement approach.

The first approach consists in measuring one face at a time, and to build equations to extrapolate the contribution of a back side illumination to the electrical values of bifacial modules. This approach implies two hypotheses:

- *Isc* (front or back) is proportional to the irradiation
- *Pmax* of the module can be expressed as a unique function of *Isc*, equation (1), wherever the photo-generation takes place at the front or at the back side.

The first hypothesis is a commonly agreed approximation, whereas the second needs to be assessed. If equation (1) is commonly used for monofacial modules, we need to verify if it is correct for bifacial modules.

$$P\max = g(Isc) \tag{1}$$

The use of the module efficiency and the normalization of this equation is common and enables the comparison of module behavior, equation (2).

$$\frac{\eta}{\eta_{STC}} = f\left(\frac{Isc}{Isc_{STC}}\right) \tag{2}$$

Fig. 2 shows the normalized efficiencies measured at INES on different modules, of very different physical characteristics.

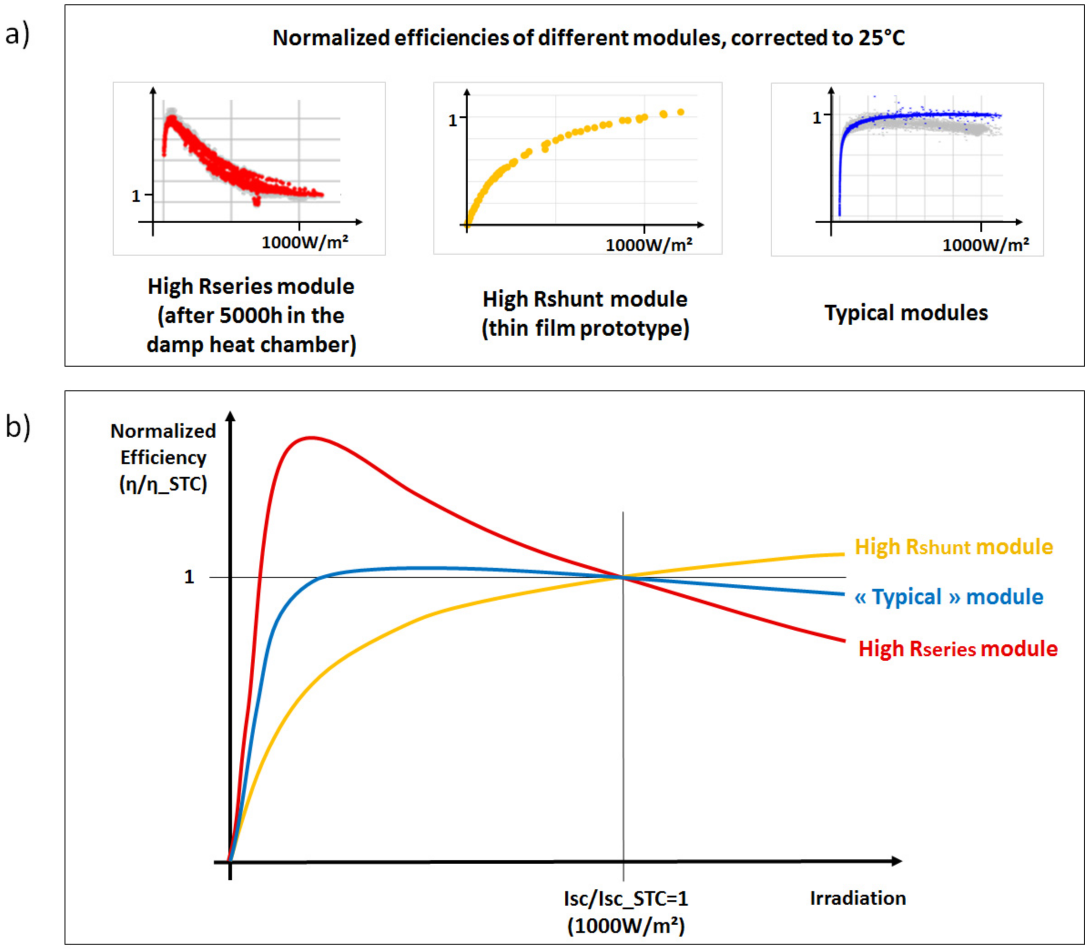

Fig. 2. (a) Normalized efficiencies of different modules measured at CEA-INES and corrected to 25°C. (b) Schematic curve of normalized efficiencies for different modules

These efficiencies are not linear functions of the irradiation as it could be approximated for *Isc*.

Most of PV laboratories already built their own equation to describe this function, in order to simulate performance (inter-comparisons have already been benchmarked in the projects PERFORMANCE Europe and SOPHIA). One challenge is also to reduce the number of flashes and characterization steps to extrapolate a relevant model.

CEA developed and applies the 'MotherPV' model [5], as described in equation (3), (4) and (5).

$$S = \frac{Isc}{Isc_{STC}} \tag{3}$$

$$f = 1 + a \cdot (S-1) + b \cdot \ln(S) + c \cdot (S-1)^2 + d \cdot \ln^2(S) \tag{4}$$

$$P\max(S) = P\max_{STC} \cdot S \cdot f(S) \tag{5}$$

To verify that the power of the module depends on Isc, whatever the proportion of current generated at the front and at the back of the module, we need to compare the normalized efficiency of the front and the back of bifacial modules.

Based on indoor flash measurements on 4 bifacial modules (manufactured at CEA-INES on one hand and commercial product on the other hand), we applied the MotherPV model (Fig. 3).

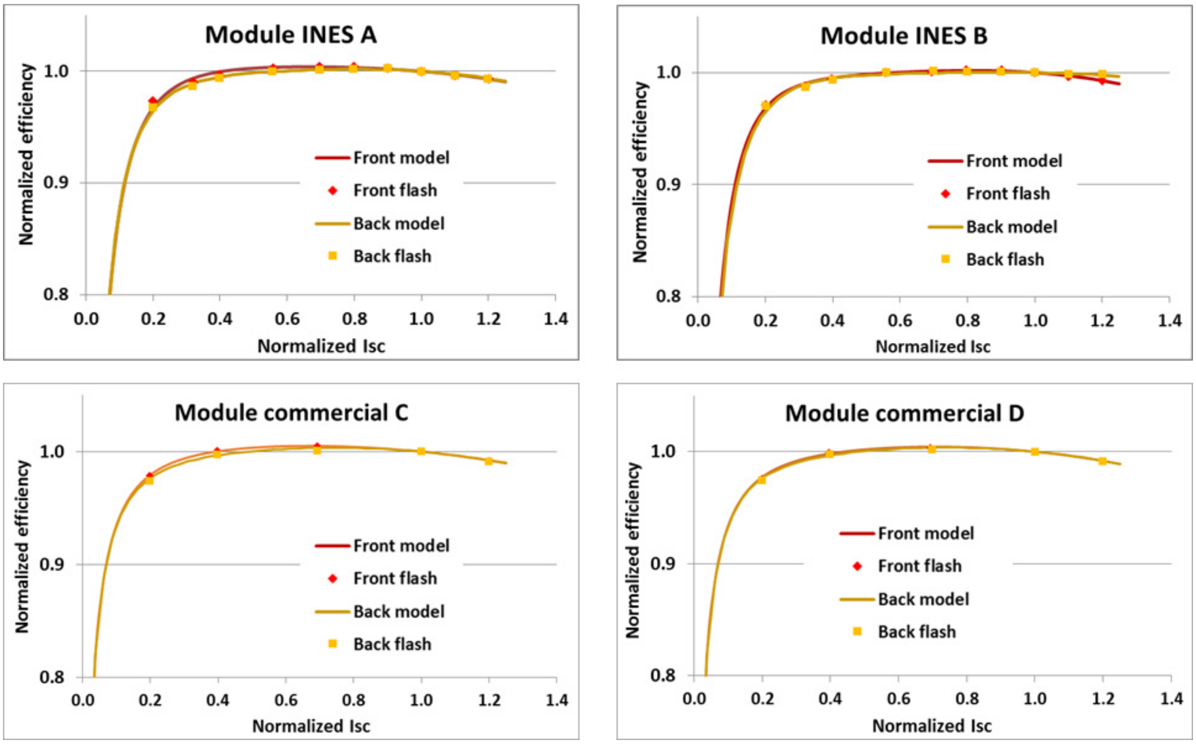

Fig. 3. Normalized efficiencies of 4 bifacial modules (results of indoor flash measurements and equivalent MotherPV models)

The meaning of Fig. 3 is that the general behavior of the modules is close to what is modeled whichever side is tested. Contributions of the series resistance and shunt resistance to front and back performance looks similar from both sides.

For the absolute values (*Pmax* and *Isc* front are different from *Pmax* and *Isc* back), the precise difference of modeled *Pmax* front and modeled *Pmax* back is calculated for every fixed *Isc* (Fig. 4).

The results are shown in Fig. 4. Relative difference ranges from -1% to +2%, and weighted average values ranges from -0.7% to +1%. These values are not negligible, but moderated by the fact that rear side contribution to the general behavior is low. Considering that 200 W/m^2 on the back only generate around 1/6 of the total current, the overall behavior should be very close to the front one, especially for these 4 modules that have deviations around 1%. However, until we have more data and understanding, this deviation represents a 1% added uncertainty on our extrapolations.

The deviation of modeled Pmax front and back are weighted by the yearly irradiances that occur at the INES PV platform in Cadarache, a South of France city with a Mediterranean climate.

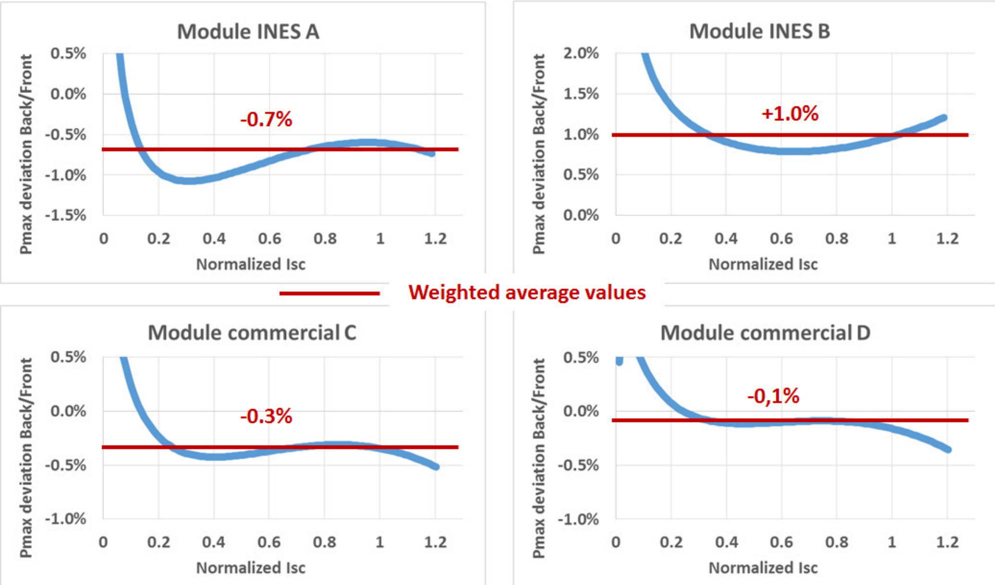

Fig. 4. Modeled Pmax deviations between front and back for every fixed Isc and their weighted average values

For these 4 modules, if we make the approximation that *Pmax* of the module is not modified by the different front and back contribution to total *Isc*, the interpretation of such a hypothesis can be described in equation (6):

$$P\max\begin{cases} Gfront = x \\ Gback = y \end{cases} \approx P\max\begin{cases} Gfront = x + y\dfrac{Isc_{STC}back}{Isc_{STC}\,front} \\ Gback = 0 \end{cases} \tag{6}$$

With the translation equation (7) and the previous equations (4), (5) and (6), we are able to extrapolate *Pmax(S)* for all *x* and *y* values, which is necessary for simulating the annual energy yield with a software.

$$S = \frac{Gfront}{1000} \tag{7}$$

In conclusion, providing data to energy yield simulators is possible from the set of flashes described in table 1(a). More flashes can be performed in order to have a more accurate model.

Table 1. (a) Minimum set of flashes to extrapolate all possible front and back contributions to the module power. (b) Mirror setup set of flashes

a)

Flash number	x	y
1	0.2	0
2	0.4	0
3	0.7	0
4	1	0
5	1.2	0
6	0	1

b)

Flash number	x	y
1	0.7	0
2	1	0
3	1.2	0
4	0	1
5 (mirrors)	1	0
6 (mirrors and filter)	1	0.227
7 (mirrors and filter)	1	0.473
8 (mirrors and filter)	1	1

However, the aim of Standard Test Conditions is not to describe *Pmax* for all x and y values, but to provide a single reference value per module that can be easily compared with other modules. Inter alia, this reference value is used as one of the inputs of the energy yield simulators, and as an input to size the system wires and the inverters current and voltage limits. The simplicity and the speed are also of importance in the choice of the method. For example, the number of flashes and the ability to perform the test with a standard flash test has to be taken into account.

The back-side of bifacial modules can provide in certain conditions up to 35% of added power, so it is relevant to build a standard close to the STC, with 1000 W/m² on one side, and up to 350 W/m² on the other side. Furthermore, in this limited range of back irradiation, the normalized efficiency looks easier to model (see the efficiency close to 1000 W/m² in Fig. 2. b). So we could do a lower number of flashes, and use linear, polynomial, or exponential models.

2.2. Second approach: simultaneous measurement of both sides

Simultaneous measurement of both sides of a bifacial module can be performed with a double-sun simulator on large size modules or with a tilted mirrors setup. Eternal Sun proposes to perform measurements with two identical sun simulators on large size modules (Fig. 5.a), while our laboratory at CEA-INES applies the tilted mirrors approach on 4 cell mini-modules (Fig. 5.b).

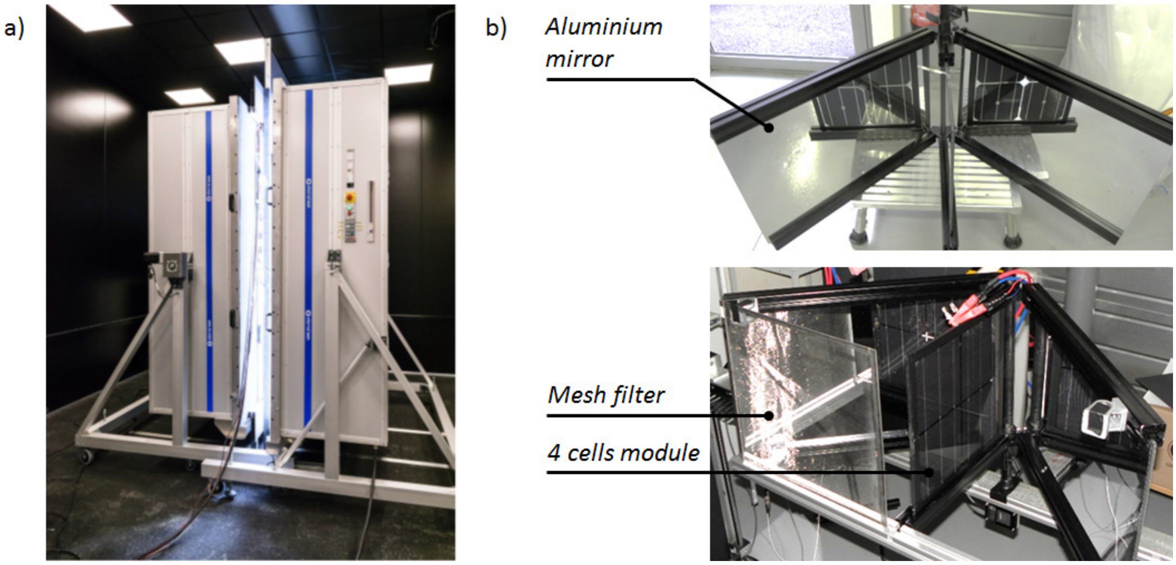

Fig. 5. (a) Eternal Sun double-sun-simulator setup (b) CEA-INES setup for 4 cells modules, with 2 tilted mirrors, mesh filters and a standard flash test [3].

Here we used a specific double illumination setup for bifacial 4 cells mini-modules [3]. The bifacial module is placed between two aluminium mirrors, and metallic grid filters with several pitches are used to attenuate the light on the backside of the module in order to mimic different albedo conditions.

We used this setup to assess if the approximations of the first approach are reliable. 8 flashes have been done on 6 bifacial modules, described in Table 2.b.

If we use a linear model starting at the value of the flash 5, based on *Pmax* bifaciality, then we obtain the deviations described in Fig. 6.a.

As we supposed in the first approach, a linear approximation can provide a good accuracy close to 1000 W/m² front and 0 to 200 W/m² back, but it is unable to be precise beyond 200 W/m² back.

The 3 first flashes of Table 3 are not enough to draw a complete MotherPV model (because it's a 4 parameter model). So we can use other simple models, for example, we model the Voc with a power function equation and the FF with a linear equation, and we managed to get a new set of extrapolated values that are closer to the measured values: Fig. 6.b shows that the deviations are lower, below 2% on all the back irradiance values.

Other models like polynomial should lead to much lower deviations and should be less dependent on the module characteristics. Logarithm models like MotherPV are more accurate but they need a larger set of flashes.

As a conclusion, performance trends models close to 1000 W/m² should be sufficient to assess bifacial performance standardization. Next step would be to assess this point with bifacial measurement of 60 cells modules on tilted mirrors setup or 2 solar simulators setup, for different technologies of bifacial modules.

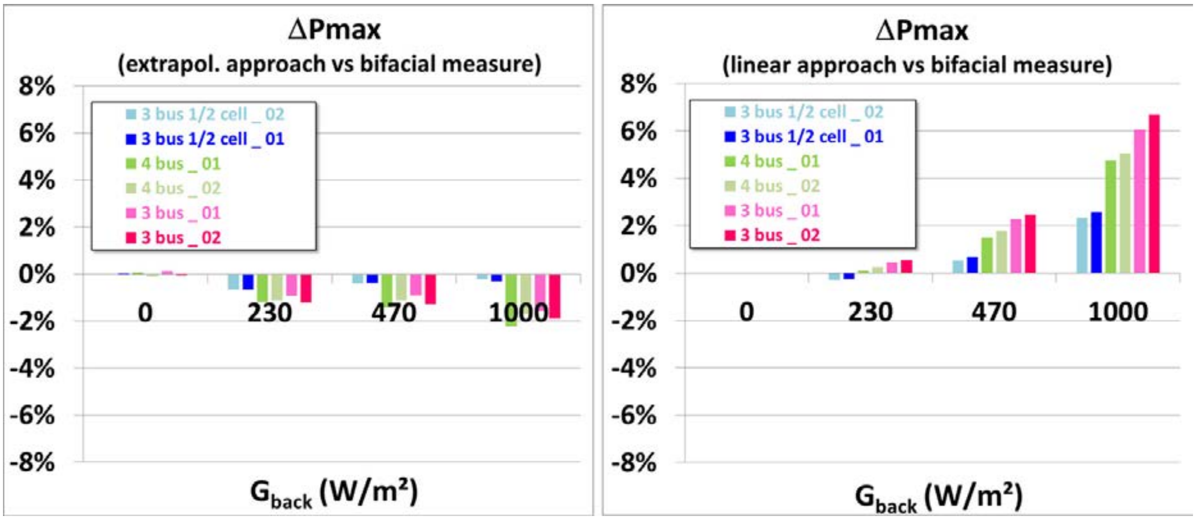

Fig. 6. (a) Deviation between a linear approximation of the power and the measurement (Gfront=1000 W/m²) (b) Deviation between a non-linear model of the power and the measurement (Gfront=1000 W/m²)

2.3. Third approach : Outdoor measurement

CEA-INES is evaluating outdoor performance of PV modules since 1983, and outdoor bifacial measurements are running since 2014 [3]. A new setup has been built in 2015, described in Fig. 7, with the study of:

- Two 60 cells bifacial modules with a black mask on the back side, for reference use
- Two 60 cells bifacial modules with a very reflective membrane fixed to the ground to maximize the back side gain (>25% according to Fig. 8).

The gain of the bifacial module compared to the monofacial is larger during cloudy days (see Fig. 8). The rear side contribution to the total power increases with an increasing part of diffuse irradiation in the total irradiation.

For the front irradiations, energy prediction software already include numerous equations and models that convert meteo data into irradiation data on the tilted front plan of the module.

The back irradiation is much more dependent on the geometrical configuration of the system and the position of the Sun rays. So ray tracing simulations and new algorithms will need to be accomplished.

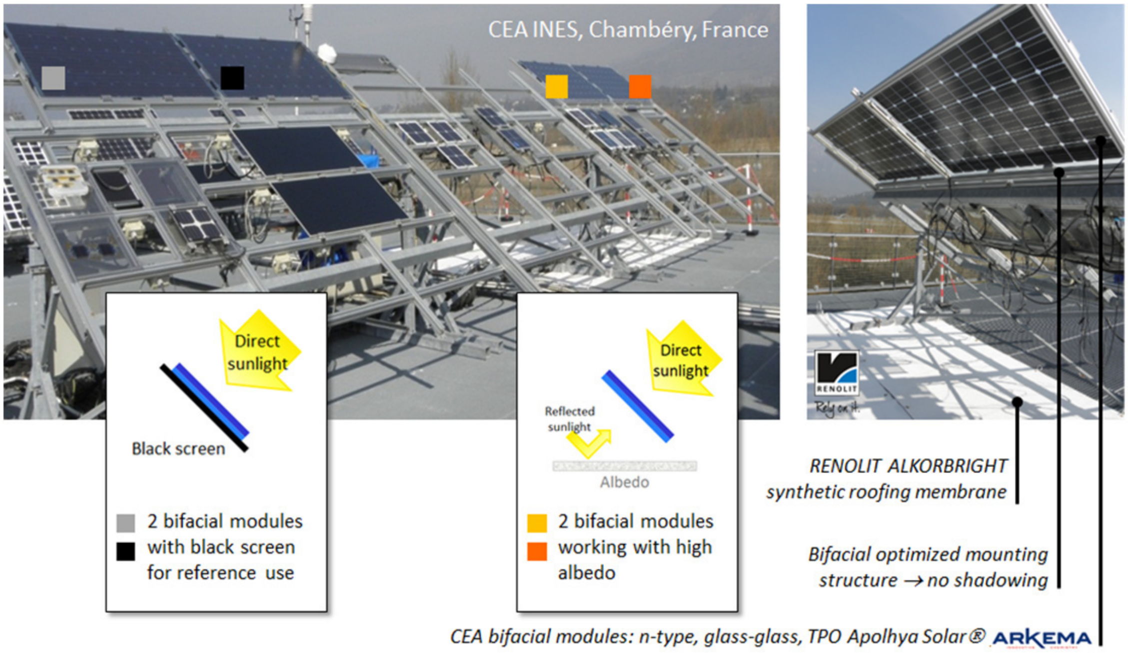

Fig. 7. Description of the CEA-INES outdoor bifacial setup

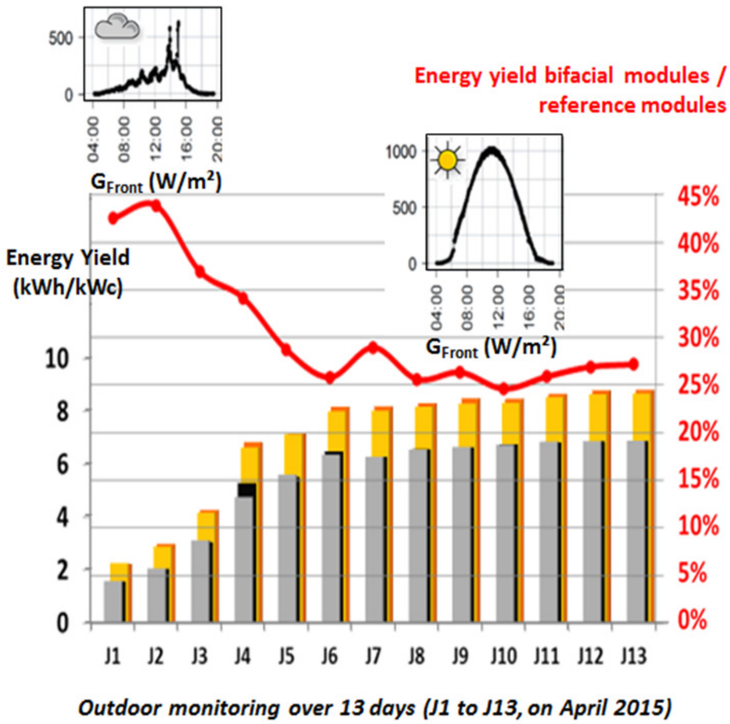

Fig. 8. Performance analysis of the outdoor setup within daily energy yields for 2 April weeks

Now we need to compare the performance indoor and outdoor, we normalize with the same *Isc* STC value, then we see a difference between the indoor and outdoor characterization of the same module (Fig. 9).

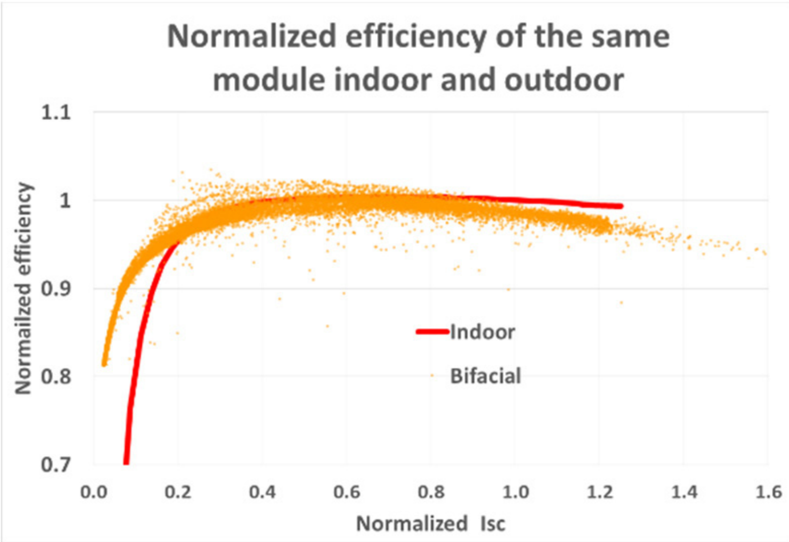

Fig. 9. Normalized efficiency of the same module indoor and outdoor

This Fig. 9 shows that indoor and outdoor behaviors cannot be superposed. This displaced curve is due to dispersion of photo-generation through the module and the presence of by-pass diodes. The back side irradiation is much more inhomogeneous than the front one. This results in a step distortions in the IV-curve, like in Fig. 10.

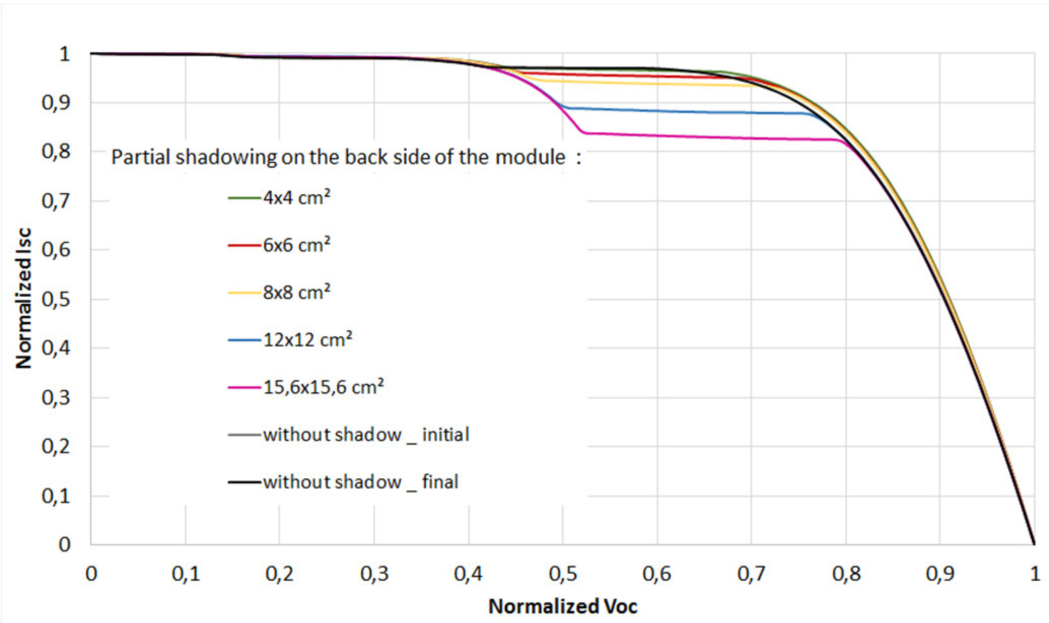

Fig. 10. Bifacial module experiment at INES. Partial shadowing on the back face of the module generates disruptive steps into the IV curve that disable the link between *Isc* and *Pmax* of the module.

Linking *Isc* to *Pmax* could be done with the estimation of the minimum string current. But this approach needs a complete ray tracing simulation tool.

For a power plant, this could be done with a geometrical determination of what is the limiting string and to simulate this string as the one which generates the additional back-irradiation contribution.

3. Conclusions

In this paper, we have shown that, for the bifacial modules studied:

- For a fix Isc value, bifacial modules behave similar when current is generated on front or rear-side
- From a 6 flashes set, *Pmax* could be extrapolated to any front and back irradiation, and a standard can be built from less flashes, depending on the accuracy that can reach models.
- Finally, the results presented in this paper show how the different approaches are complementary to help building up Standard Test Conditions and outdoor simulation tools for bifacial modules. A fast, easy and reliable standard will need deep study of the module type, comprising back and front sides analysis, and simultaneous bifacial irradiation measurement. Indoor characterization cannot be used for outdoor prediction without a realistic ray tracing simulation to evaluate the minimum back irradiance.

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